Development of Advanced Materials and Processes for State of the Art of Superconducting Magnet Technology

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Future superconducting machines will push the boundaries of what is possible with existing technologies and bring forward technologies that do not yet exist. We write to highlight the importance of developing advanced materials and processes for superconducting magnet technologies, including both the low-temperature superconducting (LTS) magnets and high-temperature superconducting (HTS) magnets, identify research needs, and express interests.

I. a. Advanced resin for Nb_3Sn accelerator magnets

In the case of Nb_3Sn accelerator magnets, large gains in magnet performance are available by substantially improving magnet quench performance and reducing required margin. It is recognized that a major component leading to magnet training and quench performance is the behavior of the magnet insulation, as the traditionally brittle behavior produces disturbances that lead to magnet quench. Development of new materials and processes for magnet insulation is essential for the next generation of high field Nb_3Sn magnets. Several approaches are available to work towards better performing insulation systems, which may be mixed and tuned to match a final magnet design. Some guiding questions can be envisioned:

1. Is it better to have more or less constraint through magnet operation [1]? Structural designs require good assumptions for conditions to hold true. Which condition set is most realistic to allow maximum magnet performance and matches simulation behavior?
2. To what extent do interface conditions affect magnet performance [2] [3]? Interface conditions appear to dominate energy release events either through adhesive failure or mechanisms such as stick-slip.
3. Are there acceptable resins that maintain high fracture toughness or ductility throughout a magnet's operation regime [4]? Increased fracture toughness should reduce the likelihood of energy release events, though it may increase the magnitude of such events. Materials that maintain some plastic behavior could mitigate this behavior entirely.
4. Can insulation processes be adapted to enable the above given the likely challenges associate with new materials? New materials or engineered materials may have substantially different handling characteristics which are not able to be implemented in present coil designs.

Many of these topics are being investigated within the framework of the US Magnet Development Program (MDP), as well as in collaboration with Composite Technology Development (CTD), Inc. Current topics of study include improved toughness and high thermal conductivity resins. Systems should be well characterized in ways that can be applied to magnet designs. These questions lead to the following directions to advance the state of the art:

- Develop surface preparation procedures to present well defined interface conditions that can be applied to Nb_3Sn superconducting magnet coils as well as other general classes of superconductors such as REBCO and Bi2212 HTS wires and cables.
- Develop tunable resin systems to homogenize the bulk material properties of the superconducting composite structure.
- Develop techniques to reduce the impact of energy release events, either through event mitigation, event avoidance, or other approaches.
- Develop insulation and impregnation processes which are robust and able to accept a large parameter space of input variation reliably.

I. b. Insulation materials for HTS magnets

In the case of the emerging HTS magnets, the development of a suitable insulation may dictate its usefulness for the future particle physics machines. Some HTS devices will enable significant improvement in power efficiency especially within high radiation environments, by replacing resistive magnets or by raising the working temperature of superconducting magnets from 4.2 K (liquid helium cooled) to 20-50 K (conduction cooled by cryocoolers). Examples include focusing solenoid magnets for positron sources for lepton accelerators and/or solenoids to capture secondary particles, such as pions, produced at targets at high intensity accelerator facilities. Taking advantage of higher critical temperature (T_c) of HTS materials, a stable operation of a magnet at a higher temperature, between 20 K and 50 K, gives multiple advantages, including improving the efficiency of refrigeration, giving extra stability to the magnets as a result of increased heat capacity at the operating point, and providing more efficient cooling because the thermal conductivity is at their maximum at around 30 K for the conductor stabilizers and heat transfer in the magnet systems. One of the keys is to develop insulation materials that are radiation hard, thin, and suitable for a tape conductor.

II. Advanced manufacturing for magnet tooling

Several emerging superconducting magnet designs can benefit from materials from addictive processing. In terms of the canted cosine theta (CCT) dipole magnet design [5] [6] [7], the mandrel is fabricated with a 3-axis CNC machine from aluminum bronze, an material that is easy to machine. New flexibility with groove designs will be permitted for REBCO magnets if an addictive processing is developed. For Bi-2212 CCT magnets, a superalloy (Inconel 600) is preferred over aluminum bronze due to its higher modulus, yielding strength, and ability to survive high temperature reactions. However, Inconel is also difficult to machine. In terms of Nb_3Sn CCT magnets, the interfacial control brought by the addictive processing may be important for minimizing the quench training found in this magnet system so far. The same goes with the stress management cosine-theta design recently proposed for Nb3Sn and Bi-2212 [8]

In general, ongoing research in this area is highly synergistic as test data should be directly applicable to magnet designs and improved simulation, while testing itself can serve as a proving ground for new advanced diagnostic techniques such as acoustic fingerprinting and evaluation of fiber-optic sensing.

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